Atmospheric Neutrino Oscillations in IceCube DeepCore

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ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Overview

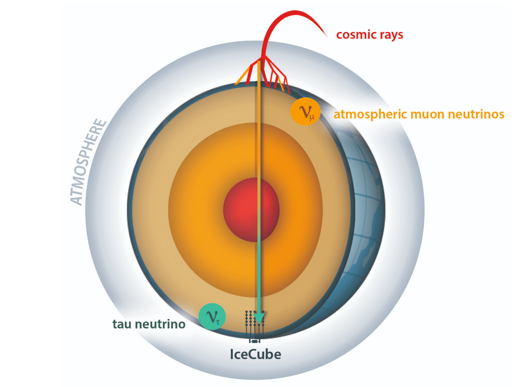
The DeepCore sub-array within the IceCube Neutrino Observatory is a densely instrumented region of Antarctic ice observing atmospheric neutrino interactions above 5 GeV.

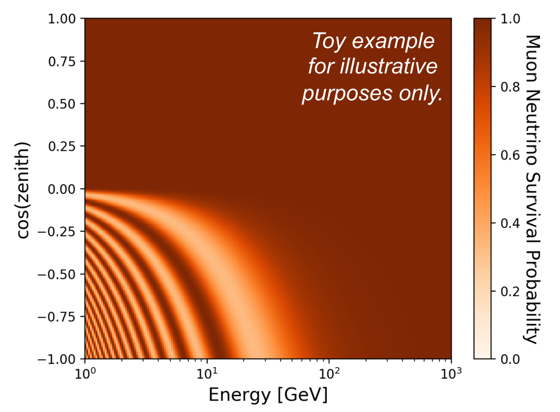
At these energies, Earth-crossing muon neutrinos have a high chance of oscillating away to tau neutrinos. These oscillations have been previously observed in DeepCore with 3 years of data. [1, 2]

Improving on previous IceCube measurements of the neutrino oscillation parameters, this analysis uses:

- 8 years of data
- improved background rejection
- new reconstruction techniques
- updated modeling of systematic uncertainties
- new particle identification using machine learning

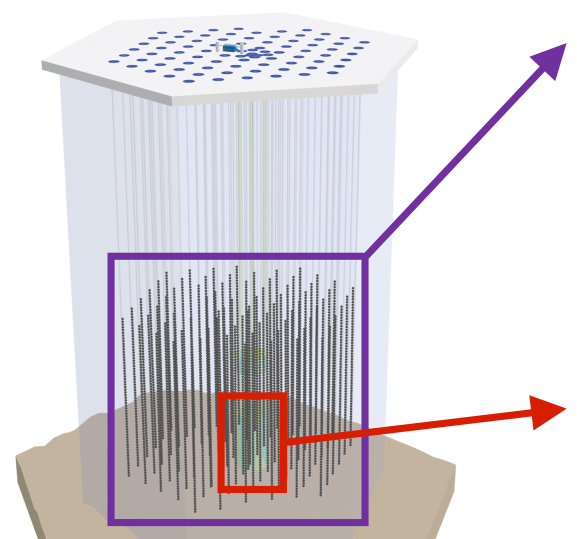
Atmospheric Neutrino Oscillations





- Cosmic rays interacting in Earth's upper atmosphere produce atmospheric neutrinos, mostly muon neutrino flavor.
- As they propagate through the Earth, they oscillate and can arrive at the detector as a different flavor.
- By looking at different directions and different energies, we can probe different L/E values. The baseline L is derived from the zenith angle and the radius of Earth.

The IceCube DeepCore Detector



IceCube

- 1 km^3 array at the South Pole
- 5160 optical sensors
- Detects Cherenkov light from charged particles passing though the glacial ice

DeepCore

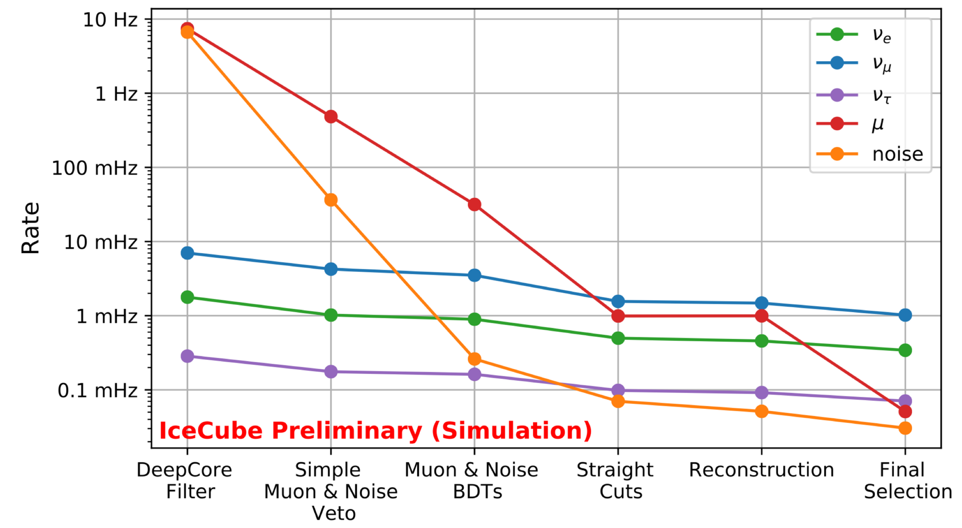
- Sub-array with denser spacing
- Detects interactions of neutrinos with energies down to 5 GeV

8-Year Analysis

Event Selection

A series of selection levels are used to reject background contamination in the final sample. The primary backgrounds are suppressed by 5 orders of magnitude, while neutrinos are only reduced by a factor of 5.

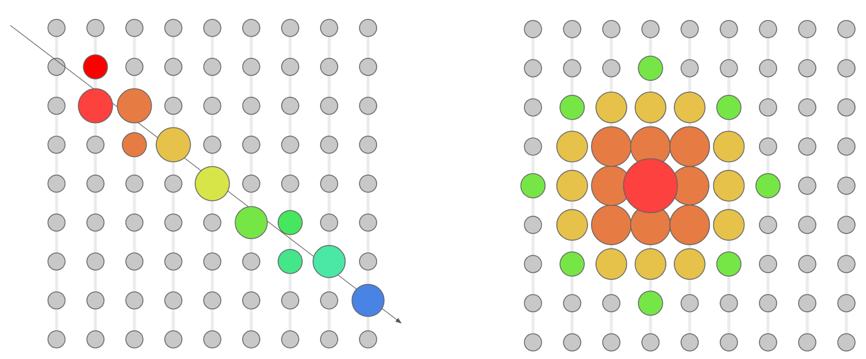
- Atmospheric muons: eliminate events with long down-going tracks that leave light in the veto regions
- Random noise: eliminate events whose hits do not appear causally connected in spacetime, or are overall too dim



Particle Identification

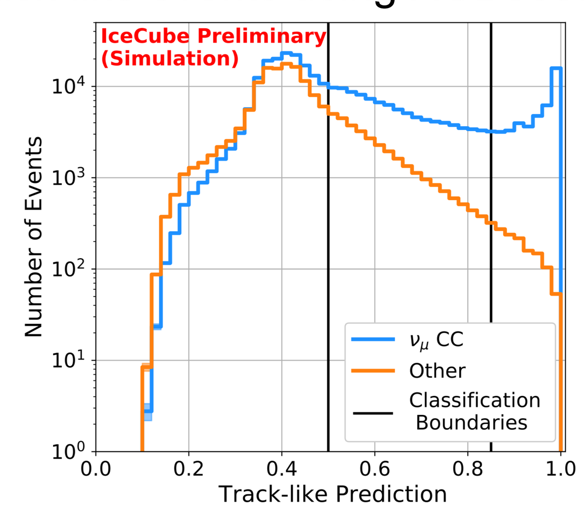
Once the neutrino events have been identified, they are categorized. A measurement of flavor oscillations relies on accurate identification of the neutrino flavor at the detector.

The two main signatures in DeepCore are tracks produced by muons in ν_μ CC interactions, and cascades produced by all other interaction types.



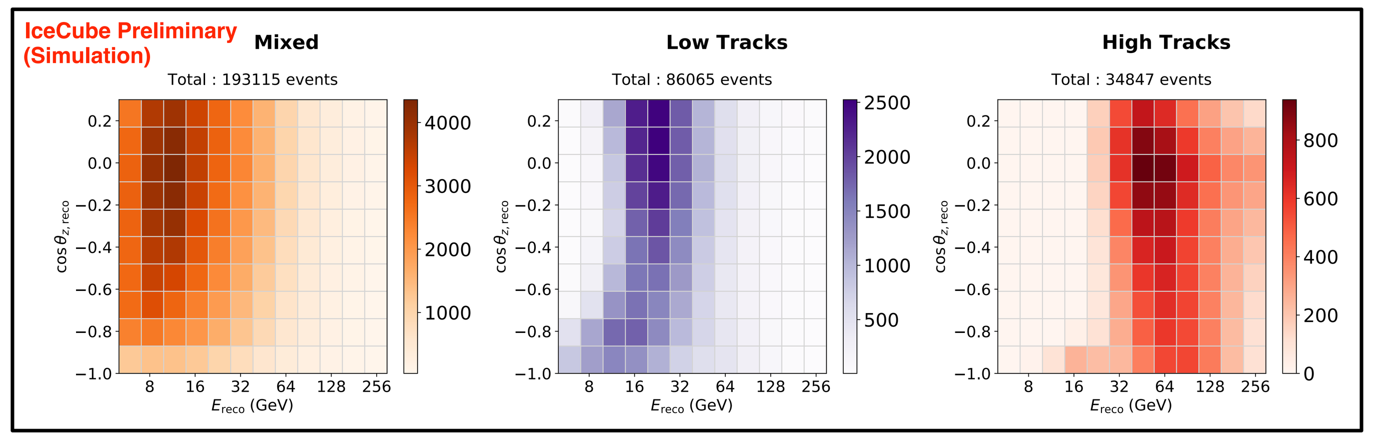
Tracks (ν_μ CC) Cascades (NC & $\nu_{e,\tau}$ CC)

A boosted decision tree (BDT) uses reconstructed quantities to separate out track-like events using XGBoost [3].



Analysis Method

Templates are created in energy, zenith, and particle identification bins to produce the expected event counts in each bin. Event counts change as physics parameters change and as systematic parameters are varied within their uncertainty bounds. The following plots show sample event distributions in the analysis bins.



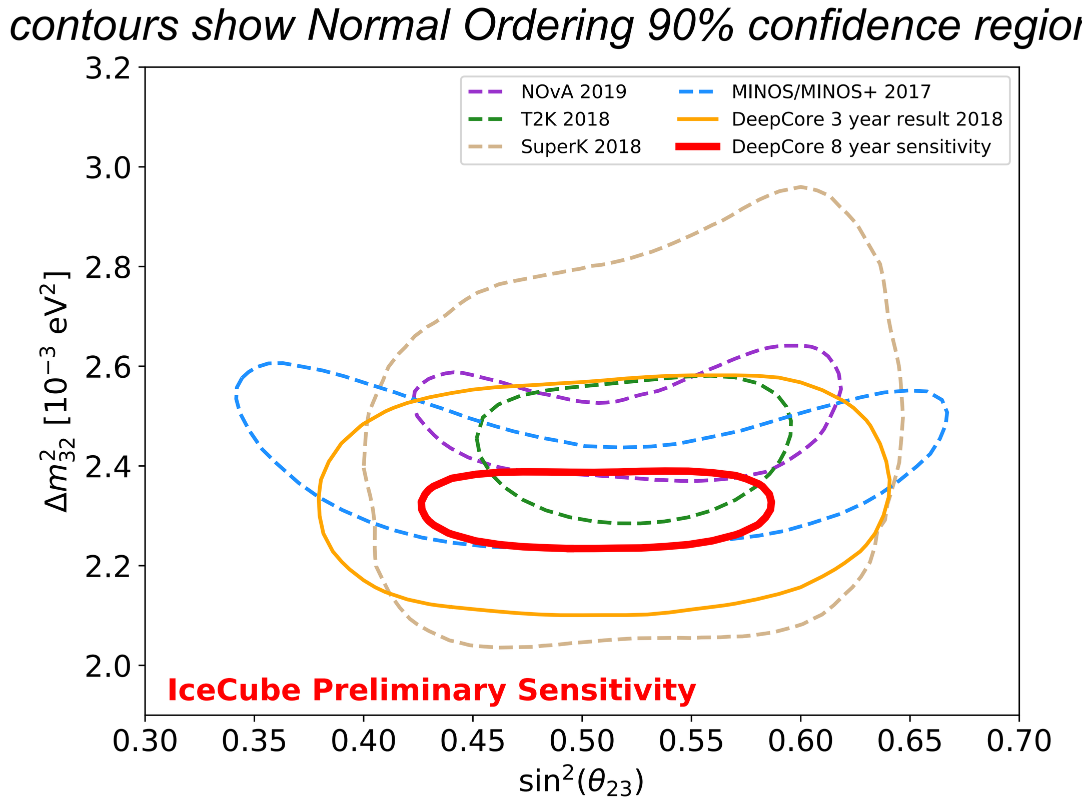
Systematic Uncertainties

- **Cosmic Ray Models & Flux Predictions:** We use the Honda model[4] for calculating the nominal flux. The uncertainties are calculated using MCEq[5] and the Barr parameterization[6].
- **Neutrino Cross Sections:** DIS cross sections are calculated using both the CSMS [7] and GENIE [8] models. A floating parameter that transforms between the two models is fit as a nuisance parameter.
- **Detector Systematics:** One of the largest sources of systematic uncertainty involves the properties of the ice in and around the detector, as well as the optical efficiency of the detector's PMTs. These properties have been parameterized and estimated using calibration data from IceCube. We include these as nuisance parameters allowing them to float with priors given by calibration data.

Analysis Sensitivity

- The estimated 90% sensitivity (assuming the same best fit point as the previous DeepCore result) is shown in red.
- The previous IceCube DeepCore result [1] is shown in gold.
- Measurements from several other experiments are shown in dotted lines: NOvA [9], T2K [10], SuperK [11], MINOS/MINOS+ [12]

All contours show Normal Ordering 90% confidence regions.



Outlook for 8-Year Analysis

Recent improvements in analysis techniques and several more years of data have led to significant improvements in sensitivity. This work is currently in collaboration review and results will be published after unblinding.

References

[1] IceCube Collaboration. Phys. Rev. Lett. 120, 071801 (2018). arXiv:1707.07081.
[2] IceCube Collaboration. Phys. Rev. D 99, 032007 (2019). arXiv:1901.05366.
[3] T. Chen and C. Guestrin. XGBoost: A Scalable Tree Boosting System. arXiv:1603.02754.
[4] M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara, and S. Midorikawa. Phys. Rev. D 92, 023004 (2015). arXiv:1502.03916.
[5] A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, and T. Stanev. EPJ Web of Conferences 99, 08001 (2015). arXiv:1503.00544.
[6] G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev. Phys. Rev. D 74, 094009 (2006). arXiv:astro-ph/0611266.
[7] A. Cooper-Sarkar, P. Mertsch, and S. Sarkar. J. High Energ. Phys. 2011, 42 (2011). arXiv:1106.3723.
[8] C. Andreopoulos, C. Barry, S. Dytman, H. Gallagher, T. Golan, R. Hatcher, G. Perdue and J. Yarba. The GENIE Neutrino Monte Carlo Generator. arXiv:1510.05494.
[9] NOvA Collaboration. Phys. Rev. Lett. 123, 151803 (2019). arXiv:1906.04907.
[10] T2K Collaboration. Phys. Rev. Lett. 121, 171802 (2018). arXiv:1807.07891.
[11] Super-Kamiokande Collaboration. Phys. Rev. D 97, 072001 (2018). arXiv: 1710.09126.
[12] Justin Evans for the MINOS and MINOS+ collaborations. 2017 J. Phys.: Conf. Ser. 888 012017. doi :10.1088/1742-6596/888/1/012017.

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